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DYNAMIC INFORMATION NETWORKS: GEOMETRY, TOPOLOGY, AND STATISTICAL LEARNING FOR THE ARTICULATION OF STRUCTURE

Daniel Rockmore
TRUSTEES OF DARTMOUTH COLLEGE

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14. ABSTRACT

The research objectives of this project were to create new mathematical tools for understanding different kinds of information networks, especially the dynamics thereof and also to import tools from geometry to analyze network dynamics. In particular, we aimed to create new mathematical frameworks for visualizing and teasing apart multiscale network dynamics. We see this as extremely relevant for the analysis of large document corpora. The primary technical approach exploits ideas from linear algebra, markov processes, diffusion networks, differential geometry, and machine learning.

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Information networks, machine learning, link prediction, hyperbolic geometry, multiscale networks, complex systems

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DYNAMIC INFORMATION NETWORKS
(FA9550-11-1-0166)
Final Performance Report
June 4, 2015

PI: Dan Rockmore (Dartmouth College)
Co-PI: Scott Pauls (Dartmouth College)
Senior Personnel:Greg Leibon (Coherent Path, Inc/Dartmouth College)
Grad Students: C. Fang and Y. Xu (Dartmouth)

The research objectives of this project were to create new mathematical tools for understanding different kinds of information networks, especially the dynamics thereof and also to import tools from geometry to analyze network dynamics. In particular, we aimed to create new mathematical frameworks for visualizing and teasing apart multiscale network dynamics. We see this as extremely relevant for the analysis of large document corpora. The primary technical approach exploits ideas from linear algebra, markov processes, diffusion networks, differential geometry, and machine learning.

Project 1: the deployment of the *partition decoupling method (PDM)*[1] in novel contexts to understand hierarchical structures in various networks.

The PDM is an analytic tool that is roughly a form of supervised learning that enables the articulation of multiscale structure in networks. In project related work we showed that the PDM could be used to discover (and novel) hidden structures in a variety of different network contexts: voting networks, personality data, and cell signaling data. This work resulted in three publications in diverse journals.

PDM and the SCN (supraschismatic celluar nucleus):

- S. Pauls, Foley NC, Foley DK, LeSauter J, Hastings MH, Maywood ES, Silver R, Differential contributions of intra-and inter-cellular mechanisms to spatial and temporal architecture of the suprachiasmaticnucleus circadian circuitry in wild-type, CRY-and VPAC2 –null mutant mice. *Eur. J. Neuroscience*. 40:3 (2014), 2528-2540.

The SCN produces various signals that generate the circadian rhythm, which can be observed through measuring concentrations of various proteins, gene expressions, etc. In this way the SCN is a living network of information transfer, but one that is not well understood. Particular questions of interest for this study is the mechanism by which the SCN 1) maintains a coherent rhythm over time and 2) adjusts the

[1] G. Leibon, S. Pauls, D. Rockmore, and R. Savell, Topological structures in the equities market network *PNAS 2008 105 (52) 20589-20594; published ahead of print December 22, 2008, doi:10.1073/pnas.0802806106*

rhythm to reflect external stimulus (e.g. overcoming jet lag, or the more gradual adjustment to seasonal changes).

Using the PDM we tested the hypothesis is that different areas of the tissue of the SCN activate in a sequence guided by both chemical and spatial factors. This sequential activation is what yields the robust circadian rhythm as well as provides a substrate on which the changes can be made. The PDM isolated the areas of the tissue that form the sequence of activation - spectral clustering is basically perfect for this. We are able to detect the coherent sets of tissue under the hypothesis that 1) we have sequential activation of the tissue and 2) that there exists an (unobserved) communication network among the cells that facilitates the regulation of the signal. This work suggested many new lines of current research.

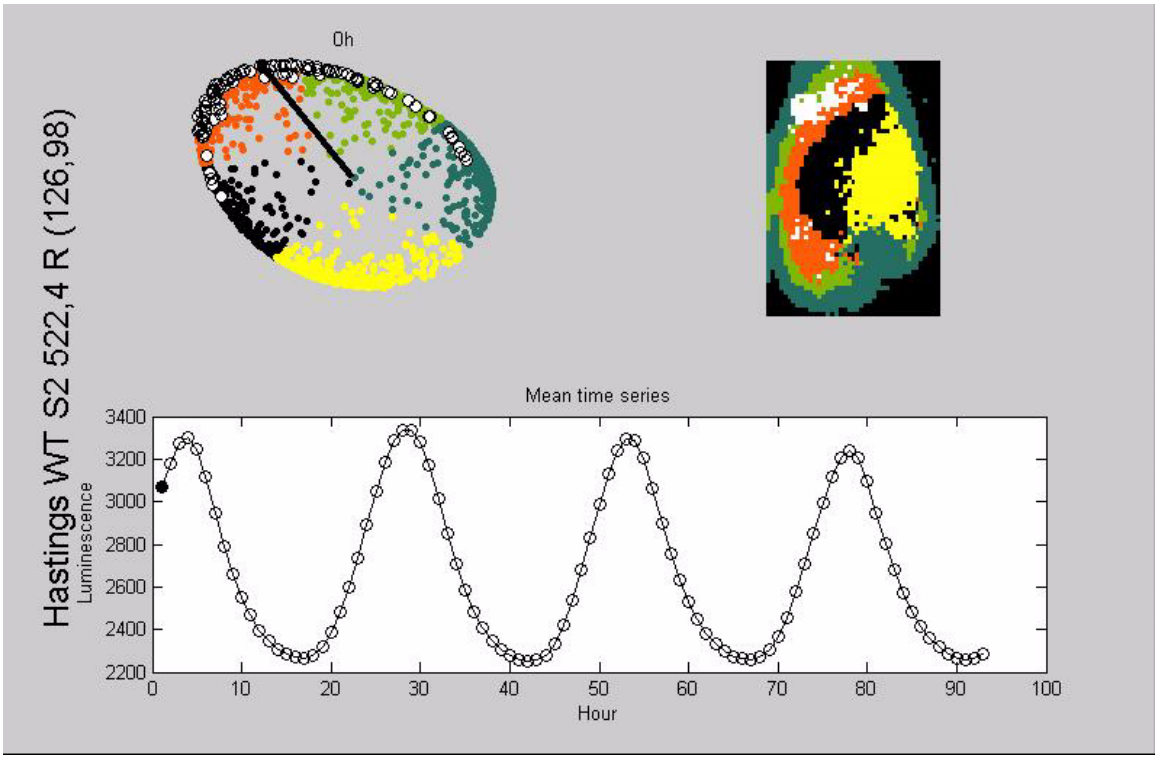

Figure 1. A still from a movie showing that for the SCN in wild type (WT) mice, shows the individual cell oscillatory behavior – sinusoidal - but that the clusters of tissue that activate sequentially are spatially contiguous and activate regularly in order over several days of recording.

B. PDM and Voting networks:

- S. Pauls, G. Leibon, and D. Rockmore, The social identity voting model: Ideology and community structures *Research & Politics 2015 2 (2) 2053168015570415*

Voting "networks" – which is to say the networks created by the correlation structure in voting records – can be used to uncover the various methods of

influence in the information structure of a legislative body, and with that the communities of influence and ideology in a society. We have a new model of voting behavior based on "social identity theory," a social sciences framework that says that identity is construct partially created and reinforced by the various circles within which one moves and to what degree one belongs. In the context of voting, we take a the body of legislator voting records (the "roll call" votes) in a given Congress to learn the social circles and then reconstruct a voting record as essentially a weighted combination of "ideal voters" per social circle. The standard model – by Poole and Rosenthal – basically assumes that the there is only one factor that matters: where a legislator lives on the liberal-conservative axis. We find that our model is a much more accurate representation of the voting behavior (as represented by the record). It also gives us the ability to drill down on the record and discover more interesting influences working within the parties. Our best example is a deeper look at the Tea Party in 112th Congress whose members are best distinguished by differing opinions on foreign policy and defense appropriations.

C. PDM and Personality

- T. Bates, S. Brocklebank, S. Pauls, and D.Rockmore, A spectral clustering approach to the structure of personality: contrasting the FFM and HEXACO models, *Journal of Research in Personality*, Volume 57, August 2015, Pages 100–109.

Two basic questions in personality research concern the dimensionality of personality – which is widely believed to be either 5 or 6 – and the content of those dimensions. Debate over these questions has largely hinged on results from factor analysis of questionnaire data. Here we use the methodology of spectral clustering – a key piece of the PDM - to test the structure of personality and compare the results with those from factor analysis. Our studies give unambiguous support for a six-domain solution using spectral clustering. Spectral clustering provides a valuable function in situations where few if any items have strong loadings on a domain. In addition to support for a sixth domain of "Honesty-Humility" the results also refocus the conventional five domains in important ways, which are discussed.

Project 2: New paradigms for information networks. In this work we bring techniques from geometry to give alternative ways for the understanding information networks. We are interested in the evolution as well as navigation (search) of such networks, especially in the case of networks built on text, which is often the basic material on which information networks are built. In the case of text, the scenario is that there is a document corpus wherein the documents are conceptually linked (e.g., research papers in a given research area, legal documents). The big questions that are then studied are (1) can we find ways to trace the flow of ideas in the documents (articulate inheritance and transmission of ideas)(2) Measure effects of the insertion of new documents into the corpus (3) can we find

ways to better articulate the influence of documents or ideas and even predict what kinds of documents/ideas have a good chance of being influential.

A. Networks with Direction

- "Orienteering in Knowledge Spaces: The Hyperbolic Geometry of Wikipedia Mathematics,: G. Leibon and D. Rockmore, PLoS ONE, 2013.

In this work we introduce the notion of a "network with directions". This is a network with a preferenced set of nodes ("directions") along with a new metric (not the usual path length metric) that is based on the idea of a "four-point probe" (inspired by a methodology in materials science) that builds on the well-known connections between network structure and electrical network theory.[2] The point of this work is to create a metric that better reflects the notion of "exploration", one that includes the idea of nodes having different global properties (as perhaps encoded in metadata) such that given that one starts at a particular node in the network, it makes sense to search in a direction of inquiry, rather than simple nearest neighbor path length exploration. The four-point probe-based metric gives a hyperbolic structure to the associated geometry and is of interest in its own right.

Our basic example in this paper is the MathWiki – the pages of Wikipedia devoted to mathematics. In this case the "directions" are the "list_of" pages – those pages that contain all the links for math pages associated with a given topic (e.g., geometry, set theory, etc.). While the list_of pages make it possible to find extremely short link-paths from one page to another, and hence from one concept to another, the link-distance does not at all reflect the conceptual distance between topics. We believe that the distance based on the four-point probe – along with the conceptual directions defined by the list_of pages, which act as "points at infinity" in the associated hyperbolic metric – does a much better job of articulating conceptual distance. This is further encoded in the geodesic bundles produced under this metric, that produce conceptual paths between pages. Our next goal is investigate a deployment of this geometry on a space of several hundred thousand judicial decisions, in order to understand the geometry of ideas in the law.

[2] See e.g., P. G. Doyle and J. L. Snell, "Random Walks and Electrical Networks," Carus Mathematical Monographs, Vol. 22, MAA, 1984.

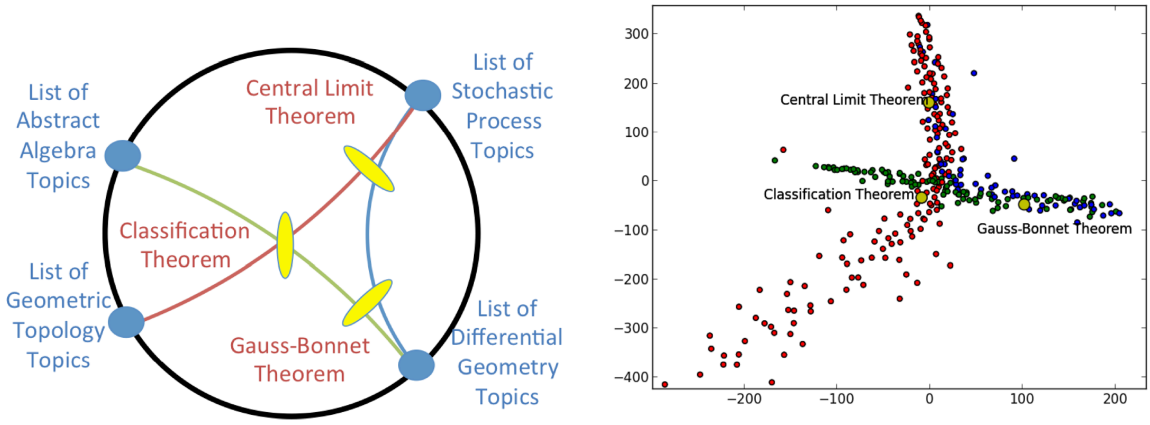

Figure 2. On the left is a cartoon of what the space of WikiMath looks like under the four-point probe geometry. Notice the curved hyperbolic triangle defined by the three (finite(points (concepts, pages) in the space. On the right is the MDS placement of the space with the pages indicated. Notice how the (thin) hyperbolic triangle is preserved, as well as the many points between them, representing "intermediate" concepts.

C. The Evolution of National Constitutions

- The Cultural Evolution of National Constitutions, D. Rockmore, D. Krakauer, T. Ginsburg, N. Foti, and C. Feng, under review (at *PNAS*).

In this work we introduce a general methology composed of a hybrid of approaches inspired by biology and genetics, to analyze general patterns of cultural inheritance and innovation, in the context a sample of 99 of the approximately 600 English constitutional texts (translations where necessary), spanning 1787-2008, available as part of the Comparative Constitutions Project.[3] In this setting it takes the form of a study of the diffusion of ideas as represented in this time-stamped text corpus. We use the basic information derived from a topic modeling of the corpus to construct cultural diffusion trees (a specific form of diffusion networks) to characterize constitutions as cultural recombinants borrowing from ancestral constitutions back to the Last Universal Common Ancestor of Constitutions (LUCAC), the US Constitution of 1787. Among the discoveries we make is that constitutions cluster into three epochs within which concepts are frequently shared. Natural metrics from the diffusion network setting give a basic taxonomy of constitutions reflecting the degree to which they borrow and transmit concepts. This framework supports the notion that culture does in fact support a genetic and particulate structure but one with significant variation in the basic patterns of descent. The methodology is quite general and could be applied to other kinds of text corpora or cultural or media artifacts.

[3] comparativeconstitutionsproject.org

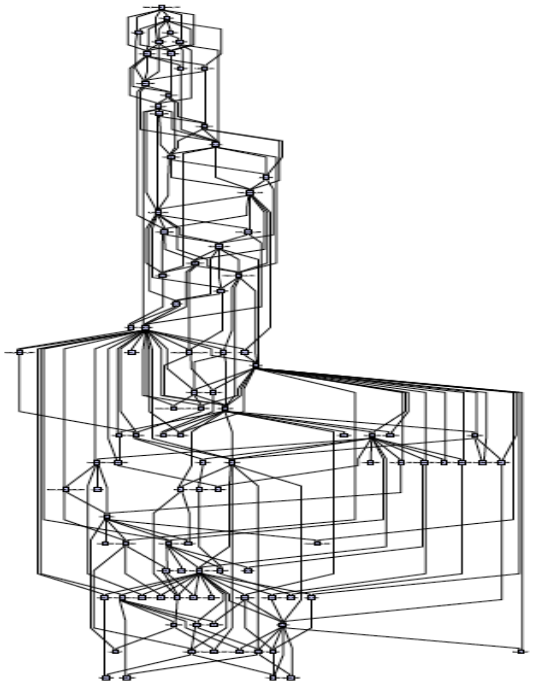

Figure 3. The diffusion tree on a sample of 99 constitutions over the years 1787-2008, built from an LDA topic modeling of the corpus.

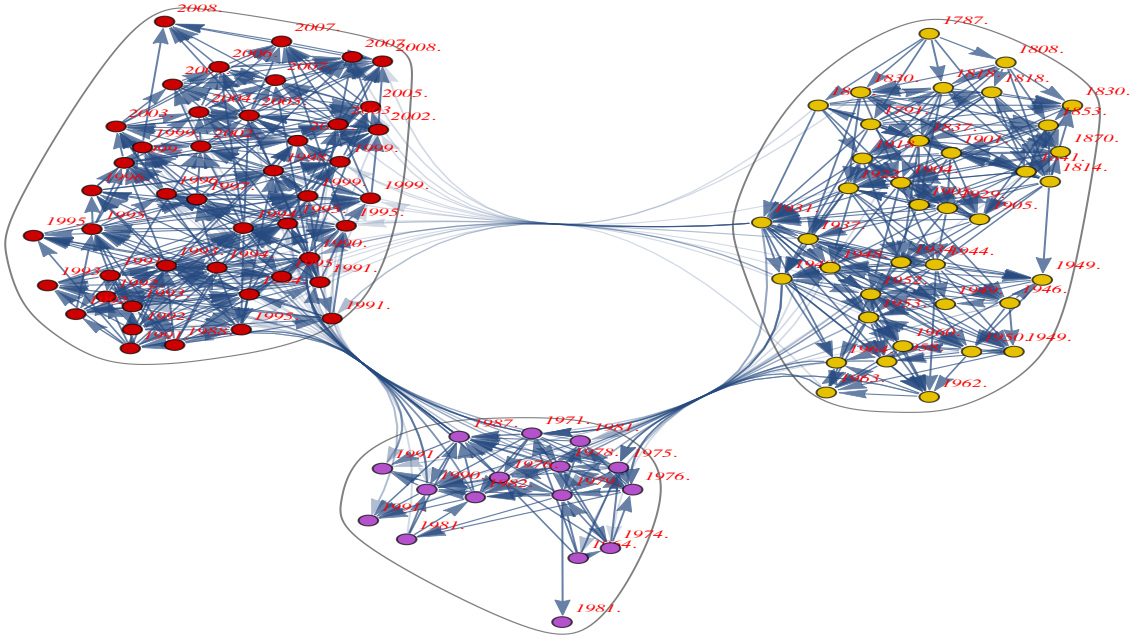

Figure 4. Clustering of the constitutional data set. The clusters are temporally localized with eras 1787, 1970 (upper right), 1971-1990 (middle), and 1991-2008 (upper left). Important "bridging" constitutions are Spain (1931) and Haiti (1987), acknowledged constitutional innovators.

D. Knowledge Networks as Landscapes.

- Bending the Law, G. Leibon, M. Livermore, A. Riddell, and D. Rockmore, preprint (2015). [Aiming for journal submission in fall 2015.]

In this work we once again consider the context of an evolving knowledge corpus. Of interest here is how certain ideas gain traction (have influence) while others fail to gain traction or fall out of favor. We see this as an interaction between the way the action of search in the corpus and the basic connectivity and similarity between the entities in the corpus. The particular context of interest is once again a corpus of documents, in this case judicial opinions, which reference each other and also have textual similarity quantified through topic similarity. Standard search mechanisms for this corpus are driven by the basic connectivity of the citation network. We extend the associated random walk to include textual similarity as well. Given the random walk we define a notion of curvature for the network (space) that depends on a new notion of distance in the space (determined through the use of the random walk). A point of "high curvature" is difficult to escape from. This in turn allows us to define a notion of "bending" – a temporal measure of the change in curvature over time at a point. In short what we discover is that points and regions around the curvature increases (becomes more positive) tend to be areas of "puddling" in the sense that in the future, they become less influential, whereas areas where the decreases (so become increasingly negative and more saddle point-like) tend to be more influential in the future. These are regions of "drainage" in the sense that ideas move through these points and regions. We test this on a corpus of Supreme Court opinions over the years 1951-2007 and find that the notions of puddling and

drainage do in fact achieve the stated effects, with these characteristics showing opinions to be either 5% more or less likely to have future impact (in a sense we make rigorous) depending on these characterizations.

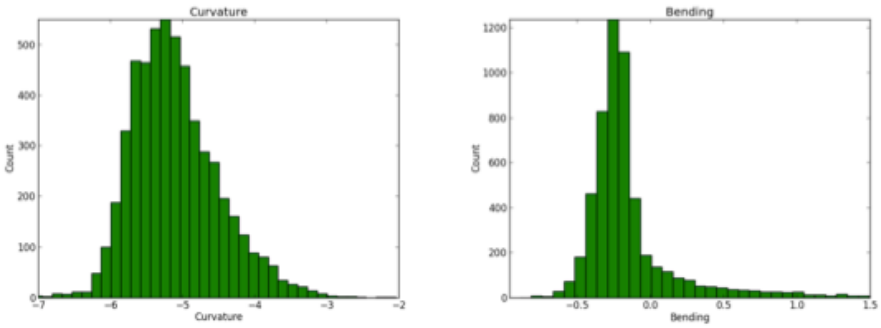

Figure 5. On the left is a histogram of the curvatures for the corpus of opinions as of 1990. Note that they are all negative, reflecting a generally locally hyperbolic structure. On the right is a distribution of the bending values, computed relative to initial time points of 1995 and 1990. I.e., this represents the way in which the curvature changes over the network in time. Note the long positive tail reflecting places where the topics become vestigial, and the shorter left "foot" of opinions around topics that are becoming more interesting in time and where one can expect a good deal of future work.

E. Link prediction in networks

- "Multi-Task Metric Learning on Network Data", C. Fang D. Rockmore, Advances in Knowledge Discovery and Data Mining, Lecture Notes in Computer Science Volume 9077, 2015, pp 317-329; Accepted to Pacific-Asia Conference on Knowledge Discovery and Data Mining (PAKDD) 2015; http://arxiv.org/abs/1411.2337
- "Sparse Coding for Key Node Selection over Networks," Y. Xu and D. Rockmore, Discovery Science, Lecture Notes in Computer Science Volume 8777, (2014), pp 337-349

In this work we consider the problem of link prediction in networks. In the first paper cited here we address link prediction via the framework of *multi-task learning* (MTL), a technique that has been shown to improve prediction performance in a number of different contexts by learning models jointly on multiple different, but related tasks. The proposed approach builds on structural metric learning and intermediate parameterization, and has efficient implementation via stochastic gradient descent. We consider two common real-world applications: citation prediction for Wikipedia articles and social circle prediction in Google+. The proposed method achieves promising results and exhibits good convergence behavior.

In the second paper we take on the issue that the size of networks now needed to model real world phenomena poses significant computational challenges. We introduce the notion on *key node selection in networks*, (KNSIN), a technique for

discovering a (much smaller) representative set of nodes able to preserve the sketch of the network. KNSIN is accomplished via a sparse coding algorithm that efficiently learns a basis set over the feature space defined by the nodes. By executing a stop criterion, KNSIN automatically learns the dimensionality of the node space and guarantees that the learned basis accurately preserves the sketch of the original node space. We demonstrate its effectiveness on experiments on two large-scale network datasets we demonstrate the effectiveness of the KNSIN algorithm.

F. Organizational networks

- R. L. Lumsdaine, D. N. Rockmore, N. Foti, G. Leibon, and J. D. Farmer, The Intrafirm Complexity of Systemically Important Financial Institutions (May 8, 2015). Presented at 2015 SYRTO Conference on Systemic Risk. Available at SSRN: http://ssrn.com/abstract=2604166 or http://dx.doi.org/10.2139/ssrn.2604166 (preparing for a fall 2015 journal submission).

Large financial organizations are both part of complex networks (e.g., the global financial system) as well as being networks themselves. In November, 2011, the Financial Stability Board, in collaboration with the International Monetary Fund, published a list of 29 "systemically important financial institutions" (SIFIs). This designation reflects a concern that the failure of any one of them could have dramatic negative consequences for the global economy and is based on "their size, complexity, and systemic interconnectedness". While the characteristics of "size" and "systemic interconnectedness" have been the subject of a good deal of quantitative analysis, less attention has been paid to measures of a firm's "complexity." In this paper we take on the challenges of measuring the complexity of a financial institution by exploring the use of the structure of an individual firm's control hierarchy as a proxy for institutional complexity. The control hierarchy is a network representation of the institution and its subsidiaries. We show that this mathematical representation (and various associated metrics) provides a consistent way to compare the complexity of firms with often very disparate business models and as such may provide the foundation for determining a SIFI designation. By quantifying the level of complexity of a firm, our approach also may prove useful should firms need to reduce their level of complexity either in response to business or regulatory needs. Using a data set containing the control hierarchies of many of the designated SIFIs, we find that between 2011 and 2013, these firms have decreased their level of complexity, perhaps in response to regulatory requirements.

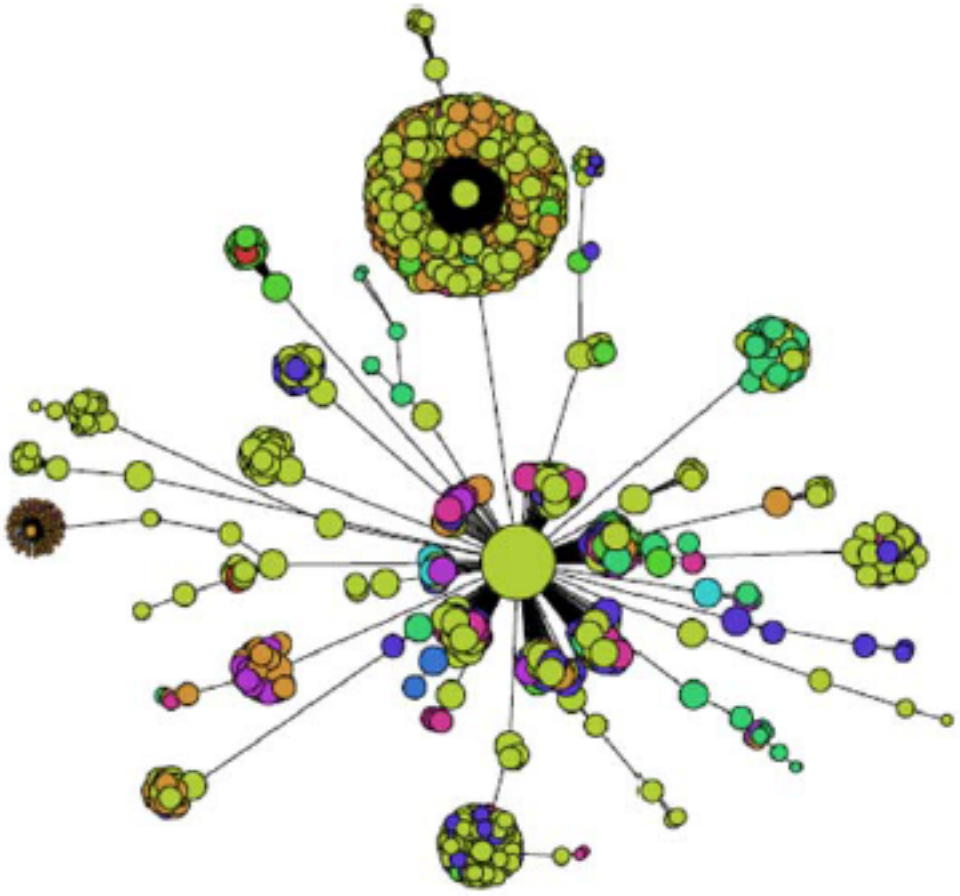

Figure 6. The tree for one of the Systemically Important Financial Institutions and its various hierarchy of subsidiaries (as determined by its control hierarchy) color-coded according to the three-digit Standard Industry Classification (SIC) code of the entities.

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Daniel N. Rockmore

Program Manager

The AFOSR Program Manager currently assigned to the award

James Lawton

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Abstract

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S. Pauls, G. Leibon, and D. Rockmore, The social identity voting model: Ideology and community structures Research & Politics 2015 2 (2) 2053168015570415

T. Bates, S. Brocklebank, S. Pauls, and D.Rockmore, A spectral clustering approach to the structure of personality: contrasting the FFM and HEXACO models, Journal of Research in Personality, Volume 57, August 2015, Pages 100–109.

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New PM: James Lawton

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LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

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